

Measurements of Ocean Waves and Surface Features using Polarimetric SAR

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LONG -TERM GOALS

Studies have shown that polarimetric SAR may be used to measure terrain slopes and surface roughness. The first goal is to extend these measurement concepts here to study slope distribution changes generated by ocean wave-current interactions such as the surface manifestations of internal waves [1]. These changes are then, in turn, used to estimate the perturbations in the ambient slope distribution that are directly caused by the ocean surface feature.

The second goal has been the measurement of directional wave spectra using polarimetric SAR (POLSAR) techniques. Measurements of ocean features and waves are conventionally done using backscatter intensity modulations. POLSAR techniques have been developed to measure wave slopes in the orthogonal SAR (azimuth/range) directions. In the techniques, feature induced changes in the polarimetric orientation/alpha angles are measured. The methods are physically based, robust, and utilize a parametrically simple modulation transfer function.

NASA/JPL/AIRSAR L-band data from California coastal waters has been used. Wave spectra measured using the new methods are compared with spectra developed using both conventional SAR intensity-based methods and National Data Buoy Center (NDBC) buoys [2].

OBJECTIVE 1: WAVE CURRENT INTERACTION MEASUREMENTS

The use of polarimetric SAR to measure changes in wave slope distributions caused by internal waves and ocean current fronts has been investigated. The basic concepts for the study have previously been used to measure both land topography and surface roughness.

The image data used in all the studies is NASA JPL/AIRSAR P-, L-, and C-band quad-pol data. AIRSAR data on internal waves was used from 1) the 1992 Joint US/Russia Internal Wave Remote Sensing Experiment (JUSREX'92) in the New York Bight, and 2) from current fronts during the Naval Research Laboratory Gulf Stream Experiment (NRL-GS'90). Extensive sea-truth was available for both experiments.

This study was motivated by the discovery that strong perturbations in the polarimetric orientation angle θ occurred in the vicinity of both types of ocean features. The AIRSAR L-band data was used for the present study. An example of an AIRSAR VV-polarization image of several internal wave packets is given in Figure 1. The observed changes in orientation angle for the same internal waves may be observed in Figure 2. The large spatial extent of the orientation angle perturbations ($>100\text{m}$ for the internal waves) made it unlikely that the effect is due to a bulk change in water height or slope. The assumption is made that wave-current interactions make the wave slope distributions asymmetric in a direction parallel to the current flow. A plot of orientation angle perturbations caused by the internal waves is given in Figure 3. The values are obtained along the propagation vector line of Figure 1. Averaging in the direction orthogonal to the propagation vector was 5 pixels. The signal / background ratio for the detection of internal waves is quite high.

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14. ABSTRACT Studies have shown that polarimetric SAR may be used to measure terrain slopes and surface roughness. The first goal is to extend these measurement concepts here to study slope distribution changes generated by ocean wave-current interactions such as the surface manifestations of internal waves [1]. These changes are then, in turn, used to estimate the perturbations in the ambient slope distribution that are directly caused by the ocean surface feature.					
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STUDY OF INTERNAL WAVE PACKETS IN THE NEW YORK BIGHT

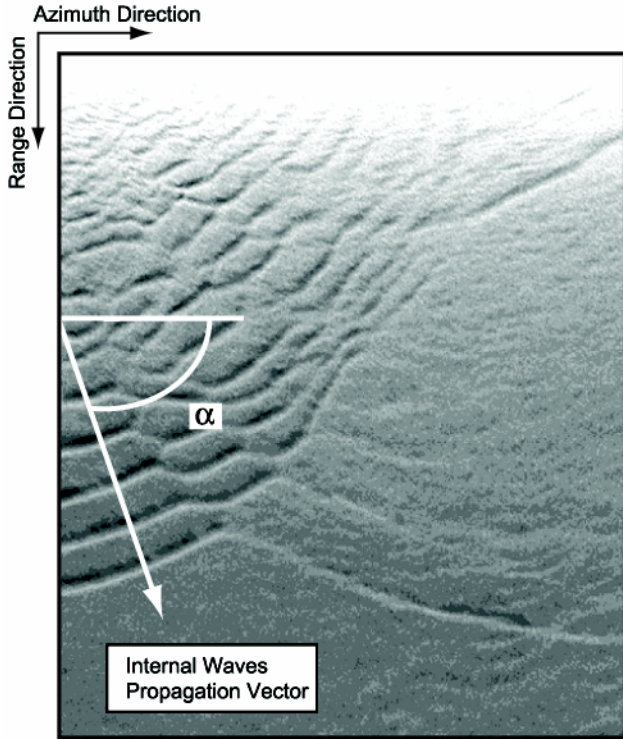


Figure 1: L-band VV-pol intensity image.

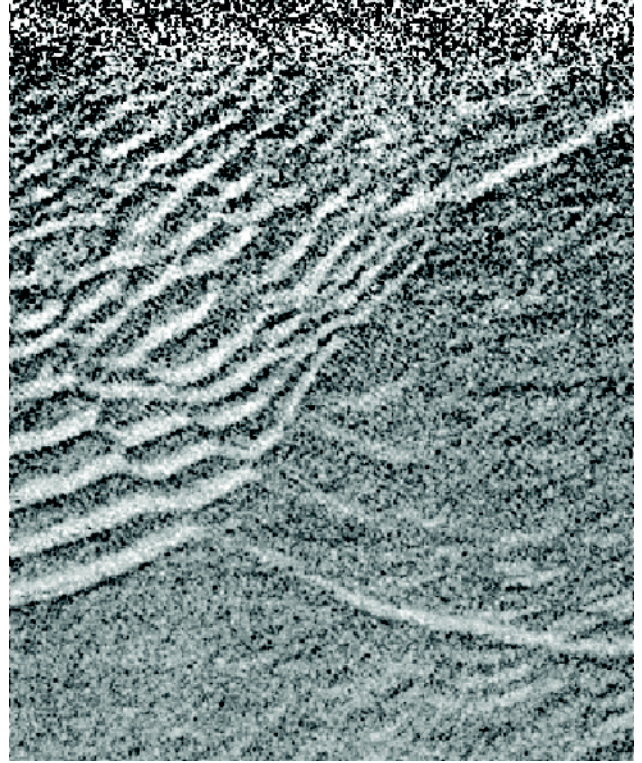


Figure 2: Orientation angle image.

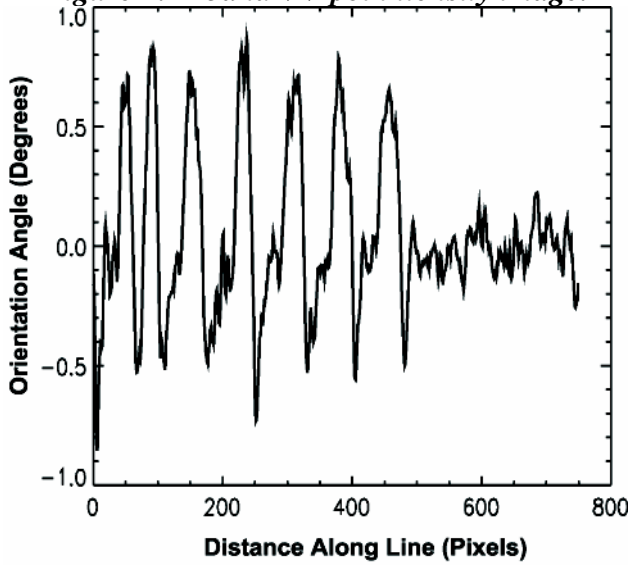


Figure 3: Orientation angle values along the propagation vector.

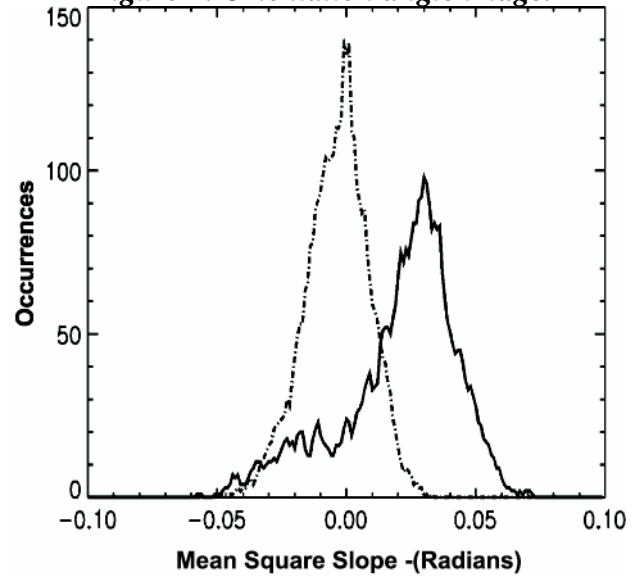


Figure 4: Distributions of wave slopes; internal wave (solid); ambient ocean (dashed).

APPROACH: WAVE SLOPE POLSAR MEASUREMENT METHODS

The current-induced asymmetry creates a mean slope that is, in turn, manifested as a mean orientation angle $\langle \tan \theta \rangle$. The relation between the orientation angle θ , wave slopes in the radar azimuth and range directions ($\tan \omega$, $\tan \gamma$) and the radar look angle ϕ is:

$$\tan \theta(\omega, \gamma) = \frac{\tan \omega}{\sin \phi - \tan \gamma \cos \phi} \quad (1)$$

And the average orientation angle is:

$$\langle \tan \theta \rangle = \int_{-\infty}^{\infty} \tan \theta(\omega, \gamma) P(\omega, \gamma) d\gamma d\omega \quad (2)$$

Where, $P(\omega, \gamma)$ is the joint probability distribution function for the surface slopes in the azimuth and range directions.

If the slopes are zero-mean but $P(\omega, \gamma)$ is skewed, then the mean orientation angle may not be zero even though the mean azimuth and range slopes are zero. It has been determined from the above equation that both the range and the azimuth slopes have an effect on the mean orientation angle. If, for instance, the long and intermediate waves are modulated by the internal wave, then both ω and γ will change locally. This will yield a non-zero mean orientation angle. Radar cross-section (σ_0) intensity perturbations, for the type of internal waves encountered in the New York Bight, have been calculated by Thompson [JHU/APL] and others. Related perturbations also occur in the ocean wave height and slope spectra. For the chosen conditions these perturbations become significantly larger for ocean wavelengths longer than about 0.6m and shorter than 6m. A histogram for the ambient ocean near the internal wave is given by the dot-dash-dot line in Figure 4. The mean square slope $\langle \beta^2 \rangle$ inferred for the perturbed area within the internal wave is 0.03 (which corresponds to 1.72°). The mean square slope is not known for this particular internal wave, but a value of this magnitude is in agreement with analysis by Lyzenga and Bennett [ERIM] for internal waves in the same area during an earlier experiment [SARSEX, 1988].

This first part of the program has investigated the effect of internal waves and current fronts on the polarimetric orientation angle. The results may provide 1) independent means for identifying these ocean features (both by orientation angle coherence changes, and 2) a method of estimating the mean value of the slope perturbations caused by the underlying wave-current interactions.

OBJECTIVE 2: MEASUREMENT OF DIRECTIONAL WAVE SPECTRA

Synthetic aperture radar images of waves on the ocean surface have been used with intensity-based algorithms to measure physical parameters such as wave slope spectra. SAR instruments operating at a single polarization measure wave induced backscatter cross-section modulations. These measurements require a parametrically complex modulation transfer function (MTF) to relate wave properties to the SAR measurements. The studies reported here investigate the feasibility of using polarimetric SAR data to measure ocean wave slopes in both the radar azimuth and range directions. In the Fourier-transform domain, this orthogonal slope information may be used to estimate a complete directional ocean wave slope (or height) spectrum. Motion-induced “velocity-bunching” effects still present difficulties for wave measurements in the azimuth direction. The advantage of using these new POLSAR algorithms is that a nearly direct physical measurement of the slope is made which does not require the use of a nonlinear, complex MTF.

Modulations of the polarization orientation angle θ are caused largely by waves traveling in the azimuth direction. A method that senses modulations of θ is used to measure wave slopes in the azimuth direction. Slopes smaller than 1° are measurable using this technique.

An eigenvector/eigenvalue decomposition parameter α (α) is used to measure wave slopes in the orthogonal range direction. Waves in the range direction cause modulation of the local incidence angle that, in turn, also modulates the value of α . From these azimuth and range slope pairs, a directional wave spectrum may be estimated.

NASA/JPL/AIRSAR L-band ocean scatter data has been used in the studies. Comparisons will be made of ocean wavespectra measured using this new POLSAR method and spectra produced from conventional National Data Buoy Center (NDBC) buoys.

According to (1), the azimuth tilts may be estimated from the shift in the orientation angle, if the range tilt is known. The orthogonal range slope can be estimated using the value of local incidence angle associated with α for each pixel. Since for the ocean surface, the tilt angles are small, the denominator in (1) may be approximated by $\sin \phi$. Thus, for the ocean surface, the azimuth slope may be written as

$$\tan \omega \cong (\sin \phi) \cdot \tan \theta \quad (3)$$

Combining the azimuth slope, $\tan \omega$ and range slope $\tan \gamma$ provides complete slope information for each image pixel.

RESULTS: ORIENTATION ANGLE (AZIMUTH DIRECTION) SPECTRA

POLSAR data can be represented for single-look complex data by a scattering matrix, or, alternatively, single-look complex, or multi-look complex data, by a covariance (or coherency) matrix. An orientation angle shift causes rotation of all these matrices about the line of sight. Since the orientation angle information is embedded in the POLSAR data, several methods have been developed to estimate azimuth slope induced orientation angles for the land and sea. The “polarization signature” method and the “circular polarization” methods have proven to be the two most effective. A complete discussion of these methods and the relation of the orientation angle to orthogonal slopes and radar parameters are given in Lee et al. [NRL]. AIRSAR data (1994) at L-band imaging a coastal area near the Gualala River in northern California was used to determine if the azimuth component of an ocean wave spectrum could be measured using orientation angle modulation. A wave system with an estimated dominant wavelength of 156m was propagating through the study-site with a wind/wave direction of 320° (NDBC Buoy, Bodega Bay, CA). Modulations in the polarization orientation angle induced by azimuth traveling ocean waves in the study area were clearly visible in the processed and the modulations were as large as ± 4 degrees.

POLARIMETRIC SAR MEASUREMENT OF WAVE SPECTRA

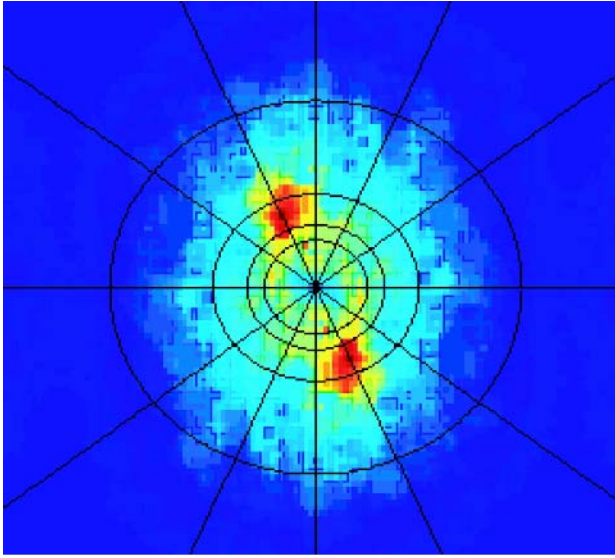


Figure 5: Orientation angle spectrum.

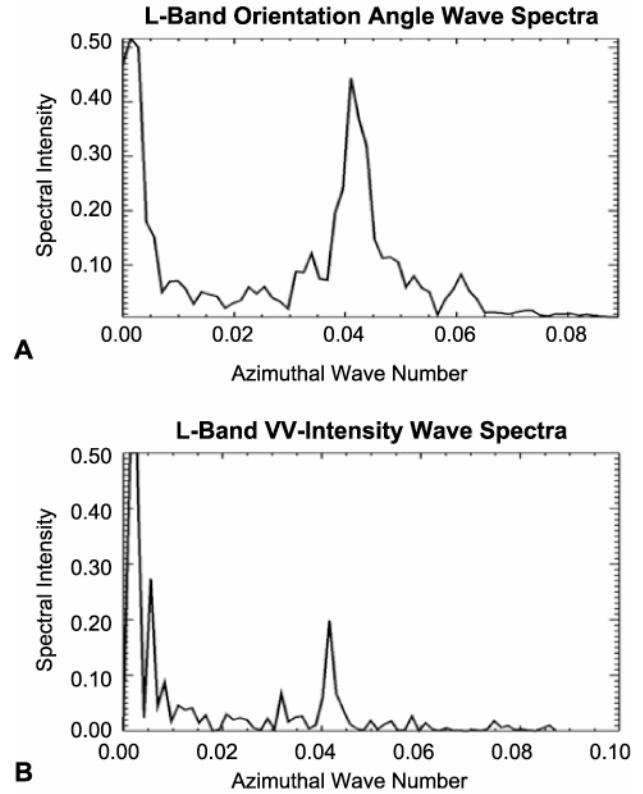


Figure 6: Plot in the propagation direction for two types of wave spectra.

Fig. 5 shows an orientation angle wave spectra with wavenumber plotted radially. The white rings are located at 50m intervals. The dominant wave, corresponding to a wavelength of 153 m, is clearly visible.

Fig. 6 (a-b): Plots of spectral intensity vs. wavenumber a) for wave-induced orientation angle modulations, and b) VV-pol intensity modulations.

Figure 6(a) presents a profile through the orientation angle spectrum made in the direction (315°) of maximum spectral energy. Figure 6(b) is a similar profile but is derived for a conventional VV-pol image SAR intensity spectrum. It is apparent that the orientation angle spectrum has a much higher dominant wave spectral peak/background ratio.

RESULTS: ALPHA PARAMETER - RANGE DIRECTION SPECTRA

Several concepts have been proposed for physically-based POLSAR measurements of ocean slopes in the range direction. These concepts were developed as a means of circumventing some of the difficulties associated with conventional backscatter intensity-based methods.

The alpha (α) parameter, developed from the Cloude-Pottier $\langle\langle H/A/\alpha \rangle\rangle$ polarimetric decomposition theorem, has desirable properties: 1) It is roll-invariant in the azimuth direction and, 2) in the range direction it is sensitive to wave-induced modulations ($\delta\phi$) in the local incidence angle ϕ . Thus, the measurements are well de-coupled.

Wave spectra may be sensed using the alpha parameter. An image of the study area may be formed with the mean of $\alpha(\phi)$ removed line by line in the range direction. An FFT of the study area results

in a wave spectra that are very similar to the spectrum of Fig. 5. This spectrum is an alpha spectrum. It can, however, easily be converted to a range wave slope spectrum.

Model studies resulted in an estimate of what the parametric relation, α vs. incidence angle ϕ , should be for an assumed Bragg-scatter model. The sensitivity (i.e., the slope of the curve of $\alpha(\phi)$) was large enough to warrant further study using real POLSAR ocean backscatter data. A second method involving the phase of HHVV* was investigated. This parameter is affected by tilts in the azimuth direction, i.e., it is not roll-invariant. A curve of the phase of HHVV* vs. ϕ was generated. This curve has considerable variability in sensitivity vs. ϕ , and is noisier than the corresponding alpha parameter curve. This method was, therefore, not used in the studies.

A spectral profile similar to Fig. 5 was developed for the alpha parameter technique and a dominant wave was measured having a wavelength of 154m and a propagation direction of 315°.

IMPACT/APPLICATIONS

Methods have been investigated which are capable of accurately measuring ocean slope distributions, wave spectra, and wave-current interactions in both the range and azimuth directions.

The new measurements are sensitive and provide nearly direct measurements of ocean slopes. The effective azimuth modulation is higher than for the intensity-based spectrum. The internal wave detection results (Objective 1) have ASW implications. The wave spectra results (Objective 2) would facilitate improved Fleet Operations through improved satellite remote sensing of sea-state.

RELATED PROJECTS

A related effort for ONR is being carried out by Dr. D. Kasilingam (U. Massachusetts, Dartmouth). His research group will file a separate Final Report. (dkasilingam@umassd.edu).

PUBLICATIONS

D.L. Schuler, R.W. Jansen, J.S. Lee and D. Kasilingam, "Polarization Orientation Angle Measurements of Ocean Internal Waves and Current Fronts using Polarimetric SAR", *IEE Proceedings on Radar, Sonar & Navigation*, EUSAR Conference Special Issue on Advances in Synthetic Aperture Radar, vol. 150, No. 5, pp.135-143 (June 2003).

D. L. Schuler, J.S. Lee, D. Kasilingam, and E. Pottier, "Measurements of Ocean Wave Slopes and Wave Spectra using Polarimetric SAR Data", Submitted to *Remote Sensing of Environment* (In press, 2003).

HONORS/AWARDS/PRIZES

This research won the Best Poster award at the international EUSAR'2002 Conference (Cologne, Germany). It has also resulted in a paper being published in the *IEE Proceedings on Radar, Sonar & Navigation* EUSAR Special Issue on Advances in Synthetic Aperture Radar (June 2003) and a manuscript being submitted to *Remote Sensing of Environment* (September 2003).